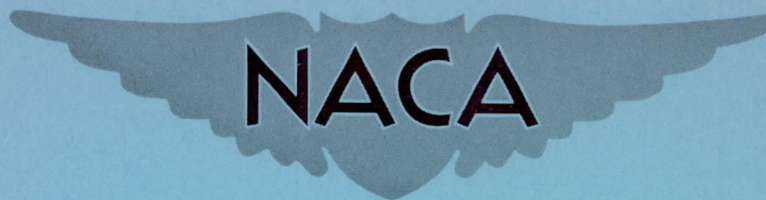


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RESEARCH MEMORANDUM

THE EFFECTS OF INCREASING THE LEADING-EDGE RADIUS AND ADDING
FORWARD CAMBER ON THE AERODYNAMIC CHARACTERISTICS
OF A WING WITH 35° OF SWEEPBACK

By Fred A. Demele and Fred B. Sutton

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Moffett Field, Calif.

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RESEARCH MEMORANDUM

THE EFFECTS OF INCREASING THE LEADING-EDGE RADIUS AND ADDING
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OF A WING WITH 35° OF SWEEPBACK

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SUMMARY

A wind-tunnel investigation has been conducted to determine the effects of a section modification on the aerodynamic characteristics of a wing with 35° of sweepback. The wing was modified by increasing the leading-edge radius of the original NACA 64A010 section and introducing a small amount of camber over the forward portion of the chord.

Lift, drag, pitching-moment, and trailing-edge-flap hinge-moment characteristics (flap undeflected) of the modified wing are compared with the characteristics of the wing without the modification. The Reynolds number was varied from 2,000,000 to 11,000,000 at a Mach number of 0.21, and the Mach number was varied from 0.21 to 0.94 at a Reynolds number of 2,000,000.

The results of this investigation reveal that the aerodynamic characteristics of the modified wing were much more sensitive to changes in Reynolds number than those of the original wing. At a Mach number of 0.21 and Reynolds numbers of 2,000,000 and 3,000,000 the modification resulted in only slight improvement in the aerodynamic characteristics of the wing. At this same Mach number but at Reynolds numbers of 7,000,000 and 11,000,000, the effect of the modification was to delay separation effects on the wing to much higher lift coefficients, the increase of lift coefficient being of the order of 50 percent at a Reynolds number of 11,000,000. This improvement was indicated by the lift, drag, pitching-moment, and flap hinge-moment data.

At a Reynolds number of 2,000,000 the modification resulted in little change in the compressibility effects on the aerodynamic characteristics of the wing. The lack of an improvement in the aerodynamic characteristics at the higher Mach numbers may be a result of the low Reynolds number at which the high-speed data were obtained.

INTRODUCTION

It has been noted in previous investigations (e.g., reference 1) that swept-back wings without twist or camber and having small leading-edge radii undergo serious changes in aerodynamic characteristics at relatively low lift coefficients. It is believed that these deficiencies may be the result of leading-edge separation associated with the use of sections having small leading-edge radii such as thin NACA 6-series sections.

Preliminary tests conducted at low speed have indicated that modifying a swept-back wing with this type of section by increasing the leading-edge radius and introducing a small amount of camber over the forward portion of the chord delayed separation to higher angles of attack. The present investigation, conducted in the Ames 12-foot pressure wind tunnel, was undertaken to extend the study of the effects of such modifications over a wide range of Reynolds numbers and to high subsonic Mach numbers.

The model wing, which was modified for this investigation, had 35° of sweepback and employed the NACA 64A010 section normal to the quarter-chord line. The modification entailed an increase in the leading-edge radius and the addition of a small amount of camber over the forward portion of the chord. As a basis for judging the effectiveness of the modification, data from reference 1 on the unmodified wing have been included herein. The data for both wings have been reduced to coefficient form on the basis of their respective wing areas.

NOTATION

The coefficients and symbols used in this report are defined as follows:

C_D	drag coefficient $\left(\frac{\text{drag}}{qS}\right)$
$C_{D_{\min}}$	minimum drag coefficient
C_{D_0}	drag coefficient at zero lift
C_h	hinge-moment coefficient $\left(\frac{\text{hinge-moment}}{2qM_A}\right)$
C_L	lift coefficient $\left(\frac{\text{lift}}{qS}\right)$
C_{L_α}	lift-curve slope $\left(\frac{dC_L}{d\alpha}\right)$, per degree

C_m	pitching-moment coefficient about the quarter point of the mean aerodynamic chord $\left(\frac{\text{pitching moment}}{qS\bar{c}} \right)$
A	aspect ratio $\left(\frac{b^2}{2S} \right)$
$\frac{L}{D}$	lift-drag ratio $\left(\frac{\text{lift}}{\text{drag}} \right)$
M	Mach number
M_A	first moment of the flap area behind the hinge line about the hinge line, feet cubed
R	Reynolds number $\left(\frac{\rho V \bar{c}}{\mu} \right)$
S	semispan wing area, square feet
V	free-stream velocity, feet per second
Y	lateral distance to mean aerodynamic chord from plane of symmetry, feet
$\frac{b}{2}$	semispan, measured perpendicular to the plane of symmetry, feet
c	chord, measured parallel to the plane of symmetry, feet
c'	chord of basic wing, measured perpendicular to quarter-chord line, feet
$\bar{c}$	mean aerodynamic chord $\left(\frac{\int_0^{b/2} c^2 dy}{\int_0^{b/2} c dy} \right)$, feet
c_f'	chord of the flap behind the hinge line, measured perpendicular to the hinge line, feet
q	free-stream dynamic pressure $\left(\frac{1}{2} \rho V^2 \right)$, pounds per square foot
y	lateral distance from plane of symmetry, feet
α	angle of attack, degrees
μ	absolute viscosity, slugs per foot-second
ρ	density of air, slugs per cubic foot

MODEL AND APPARATUS

The model used in this investigation was the semispan wing used in the tests reported in reference 1 with the NACA 64A010 airfoil section (normal to the quarter-chord line) modified by increasing the leading-edge radius from 0.687- to 1.600-percent chord of the basic NACA 64A010 section and introducing a small amount of camber over the forward portion of the chord. The resulting mean camber line resembled the NACA 240 with the camber reduced to correspond to a design lift coefficient of 0.1. The basic wing had the quarter-chord line swept back 35° , a taper ratio of 0.5, and an aspect ratio of 4.5. The modification made to the wing is shown in figure 1, and the coordinates for the NACA 64A010 airfoil section and the revised leading edge are shown in table I.

The model was equipped with a full-span, radius-nose, sealed, trailing-edge flap. The chord of the flap was 30 percent of the chord of the basic airfoil section, normal to the quarter-chord line. Details of the flap are shown in figure 1.

The wing was constructed of solid steel and the flap of aluminum alloy. The wing was modified by building up the forward 20 percent, mainly on the lower surface, with a tin-bismuth alloy and recontouring to the coordinates shown in table I.

The model was mounted vertically with the wind-tunnel floor serving as a reflection plane as shown in figure 2. The turntable upon which the model was mounted was directly connected to the force-measuring apparatus. The flap hinge moments were measured with a resistance-type electric strain gage mounted beneath the turntable cover plates.

TESTS

To determine independently the effects of Reynolds number and Mach number on the aerodynamic characteristics of the modified wing, the investigation was conducted at Reynolds numbers from 2,000,000 to 11,000,000 at a Mach number of 0.21 and at Mach numbers from 0.21 to 0.94 at a Reynolds number of 2,000,000. Lift, drag, pitching moment, and hinge moment were measured through an angle-of-attack range from -10° to 24° , except at high Mach numbers where wind-tunnel power limitations prevent testing at the higher angles of attack. All data were taken with the flap undeflected.

CORRECTIONS

The data have been corrected for the effects of tunnel-wall interference, including constriction due to the presence of the tunnel walls, and for model-support tare forces. Deflection of the wing and of the flap due to aerodynamic loading was negligible so no correction has been applied for the effects of aeroelastic deformation.

Tunnel-Wall Interference

Corrections to the data for the effects of tunnel-wall interference have been evaluated by the methods of reference 2. The corrections added to the drag coefficient and to the angle of attack were

$$\Delta\alpha = 0.329 C_L, \text{ degrees}$$

$$\Delta C_D = 0.00502 C_L^2$$

The pitching-moment and hinge-moment data were not corrected since the corrections would have been extremely small.

Constriction Effects

Corrections applied for the constriction effects due to the presence of the tunnel walls were computed by the method of reference 3. The corrections have not been modified to allow for the effect of sweep. The following table shows the magnitude of the corrections to Mach number and dynamic pressure:

<u>Corrected Mach number</u>	<u>Uncorrected Mach number</u>	<u>$\frac{q_{\text{corrected}}}{q_{\text{uncorrected}}}$</u>
0.210	0.210	1.001
.600	.600	1.001
.800	.798	1.002
.850	.848	1.003
.900	.896	1.005
.930	.923	1.008
.940	.932	1.009

Tares

A correction to the drag data was made to allow for forces on the exposed surface of the turntable. The variation of turntable drag with Mach number and Reynolds number was determined from tests with the model removed from the tunnel. Subsequent to the tests reported in reference 1, revisions have been made to the wind-tunnel turntable which have altered the drag tares slightly from those previously presented in reference 1. Turntable drag coefficients, based on the area of the semi-span wing, are presented in the following table:

<u>M</u>	<u>$R \times 10^{-6}$</u>	<u>C_D tare</u>
0.21	11.0	0.0050
.21	7.0	.0052
.21	3.0	.0055
.21	2.0	.0055
.60	2.0	.0065
.80	2.0	.0072
.85	2.0	.0075
.90	2.0	.0078
.93	2.0	.0080
.94	2.0	.0081

No attempt was made to evaluate tares due to possible interference effects between the model and the turntable, but they were believed to be small.

RESULTS AND DISCUSSION

To show the effectiveness of the modification, the aerodynamic characteristics of the modified wing are compared with those of the basic wing of reference 1.

Effects of Reynolds Number

General aerodynamic characteristics.— Lift, pitching-moment, drag, and hinge-moment coefficients are presented in figure 3 for Reynolds numbers from 2,000,000 to 11,000,000 at a Mach number of 0.21. It can be seen that, while the aerodynamic characteristics of the basic wing were moderately sensitive to changes in Reynolds number, this sensitivity was greatly increased as a result of the modification. At Reynolds numbers of 2,000,000 and 3,000,000 the modification effected only a slight improvement in the characteristics of the basic wing. At Reynolds

numbers of 7,000,000 and 11,000,000 the effect of the modification was to increase the lift coefficient at which separation effects resulted in large changes in the wing characteristics, the increase of lift coefficient being of the order of 50 percent at a Reynolds number of 11,000,000. This delay of separation to higher lift coefficients by the modification was reflected in an increase in the lift coefficient at which the abrupt forward shift of the aerodynamic center occurred, as shown in figure 3(b). This forward shift in the aerodynamic center is believed to be the result of changes in the spanwise distribution of load occurring as a result of separation on the outer portions of the wing. At a Reynolds number of 2,000,000, this sudden instability occurred at a lift coefficient of 0.77 as compared to 0.60 for the basic wing; at the highest Reynolds number of the test (11,000,000), the abrupt forward shift of the aerodynamic center occurred at a lift coefficient of 1.18 ($C_{L_{max}}$) as compared to a value of 0.80 ($0.9 C_{L_{max}}$) for the basic wing.

The reduction in drag effected by this delay of separation can be seen in figure 3(c). At Reynolds numbers of 2,000,000 and 3,000,000 the modification caused decreases in drag above a lift coefficient of about 0.50; at Reynolds numbers of 7,000,000 and 11,000,000, large reductions in drag were evident at lift coefficients above about 0.65.

The effect of the modification on the hinge-moment coefficients of the flap is shown in figure 3(d). At Reynolds numbers of 2,000,000 and 3,000,000, the modification had little effect on the flap hinge moments. However, at Reynolds numbers of 7,000,000 and 11,000,000, the angle-of-attack range over which the hinge-moment curves remained essentially linear was substantially increased as a result of the modification. Thus it is apparent that under these conditions the modification was highly effective in alleviating the separation effects responsible for the severe upfloat tendency of trailing-edge flaps on swept-back wings.

Lift-drag ratio.— Presented in figure 4 is the lift-drag ratio as a function of lift coefficient for various Reynolds numbers. These data reflect the drag reductions at the higher lift coefficients which were noted in figure 3(c). The modification slightly increased the maximum lift-drag ratio at low Reynolds numbers, but had little influence on the maximum value at the highest Reynolds number.

Drag due to lift.— The effects of Reynolds number on the drag due to lift $C_D - C_{D_0}$ of the modified wing and of the basic wing are presented in figure 5. Also shown in this figure is the calculated induced drag coefficient for a wing having the same aspect ratio (4.5) as the basic wing and an elliptical span load distribution, $C_{D_i} = C_L^2 / \pi A$. At a Reynolds number of 11,000,000, $C_D - C_{D_0}$ of the modified wing did not greatly exceed the induced drag for elliptic loading until maximum lift was attained. At the same Reynolds number, $C_D - C_{D_0}$ of the basic wing increased abruptly at only 75 percent of its maximum lift. At Reynolds numbers of 2,000,000 and 3,000,000, $C_D - C_{D_0}$ for the basic wing

increased rapidly at relatively low lift coefficients, this rapid increase being delayed to slightly higher lift coefficients as a result of the modification. If the rapid drag rise is taken as a measure of the lift coefficient at which flow separation first occurred on the wing, the effect of the modification was to delay separation at a Reynolds number of 11,000,000 to a lift coefficient almost 75 percent higher than that for the basic wing.

Effects of Mach Number

General aerodynamic characteristics.— Lift, pitching-moment, drag, and hinge-moment coefficients are presented in figure 6 for Mach numbers from 0.21 to 0.94 at a Reynolds number of 2,000,000. Although the results show only minor changes in the wing characteristics due to the modification, it should be emphasized that these data were obtained at a Reynolds number of 2,000,000 and are probably subject to the large-scale effect previously noted with the low-speed data.

At Mach numbers of 0.21 and 0.60, the modification increased slightly the lift coefficient at which separation occurred on the wing. This is indicated by the lift, drag, and pitching-moment data of figure 6. At Mach numbers of 0.80 and above, the modification resulted in virtually no improvement in the aerodynamic characteristics of the wing. The negative value of the pitching-moment coefficient at zero lift and the negative angle of attack for zero lift, which resulted from the forward camber, increased with increasing Mach number. Generally, the modification had little effect on the angle of attack at which the large increase of flap hinge moment occurred.

Lift-curve slope.— The variation of lift-curve slope (measured through $C_L = 0$) with Mach number is shown in figure 7. The effects of Mach number were similar for both the basic wing and the modified wing; the lift-curve slope gradually increased up to a Mach number slightly greater than 0.90, and then abruptly decreased with further increase in Mach number.

Aerodynamic center.— Figure 7 also shows the effect of Mach number on the location of the aerodynamic center (measured through $C_L = 0$). The effects of compressibility were similar for the two wings; the aerodynamic center remained essentially fixed up to a Mach number of 0.85 and rapidly moved rearward with further increase in Mach number. At Mach numbers up to 0.85 the aerodynamic center of the modified wing was 1 to 3 percent of the mean aerodynamic chord ahead of the aerodynamic center of the basic wing.

Minimum drag.— Also presented in figure 7 is the variation of minimum drag coefficient with Mach number. At a Mach number of 0.21 the modified wing had a minimum drag coefficient of approximately 0.0060 as

compared to approximately 0.0050 for the basic wing. These values increased slightly with Mach number up to a Mach number of about 0.90 above which the drag coefficients for both wings increased rapidly. At a Mach number of 0.94, the basic wing showed a higher minimum drag coefficient than did the modified wing. While the reason for the higher minimum drag of the basic wing at this Mach number is unknown, it should be mentioned that the choking Mach number of the tunnel is only slightly greater than 0.94. The Mach number for drag divergence (Mach number at which $\partial C_{D_{min}}/\partial M = 0.10$) was approximately 0.92 for the modified wing as compared to about 0.91 for the basic wing.

CONCLUSIONS

Tests have been conducted of a wing having 35° of sweepback and an aspect ratio of 4.5 to determine the effect of modifying the original NACA 64A010 section by increasing the leading-edge radius and concurrently introducing a small amount of camber over the forward portion of the chord. A comparison of the aerodynamic characteristics (flap undeflected) of the modified wing with those of the basic wing indicates the following conclusions:

1. Whereas the aerodynamic characteristics of the basic wing were somewhat sensitive to changes in Reynolds number at a constant Mach number of 0.21, this sensitivity to scale effect was greatly increased as a result of modification.
2. At a Mach number of 0.21 and a Reynolds number of 11,000,000, modifying the wing resulted in approximately a 50-percent increase in the lift coefficient at which flow separation caused large changes in the wing characteristics. This improvement was indicated in the lift, drag, pitching-moment, and flap hinge-moment data.
3. At Reynolds numbers of 7,000,000 and 11,000,000, the angle-of-attack range over which the hinge-moment curves remained essentially linear was substantially increased as a result of the modification.
4. At a Reynolds number of 2,000,000, the modification effected only a slight improvement in the aerodynamic characteristics of the wing at Mach numbers of 0.21 and 0.60, and virtually no improvement at Mach numbers above 0.60. The lack of greater improvement may be a result of the low Reynolds numbers at which these data were obtained.

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Moffett Field, Calif.

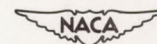
REFERENCES

1. Tinling, Bruce E., and Dickson, Jerald K.: Tests of a Model Horizontal Tail of Aspect Ratio 4.5 in the Ames 12-Foot Pressure Wind Tunnel. I.—Quarter-Chord Line Swept Back 35° . NACA RM A9G13, 1949.
2. Sivells, James C., and Deters, Owen J.: Jet-Boundary and Plan-Form Corrections for Partial-Span Models With Reflection Plane. End Plate, or No End Plate in a Closed Circular Wind Tunnel. NACA Rep. 843, 1946.
3. Herriot, John G.: Blockage Corrections for Three-Dimensional-Flow Closed-Throat Wind Tunnels, With Consideration of the Effect of Compressibility. NACA RM A7B28, 1947.

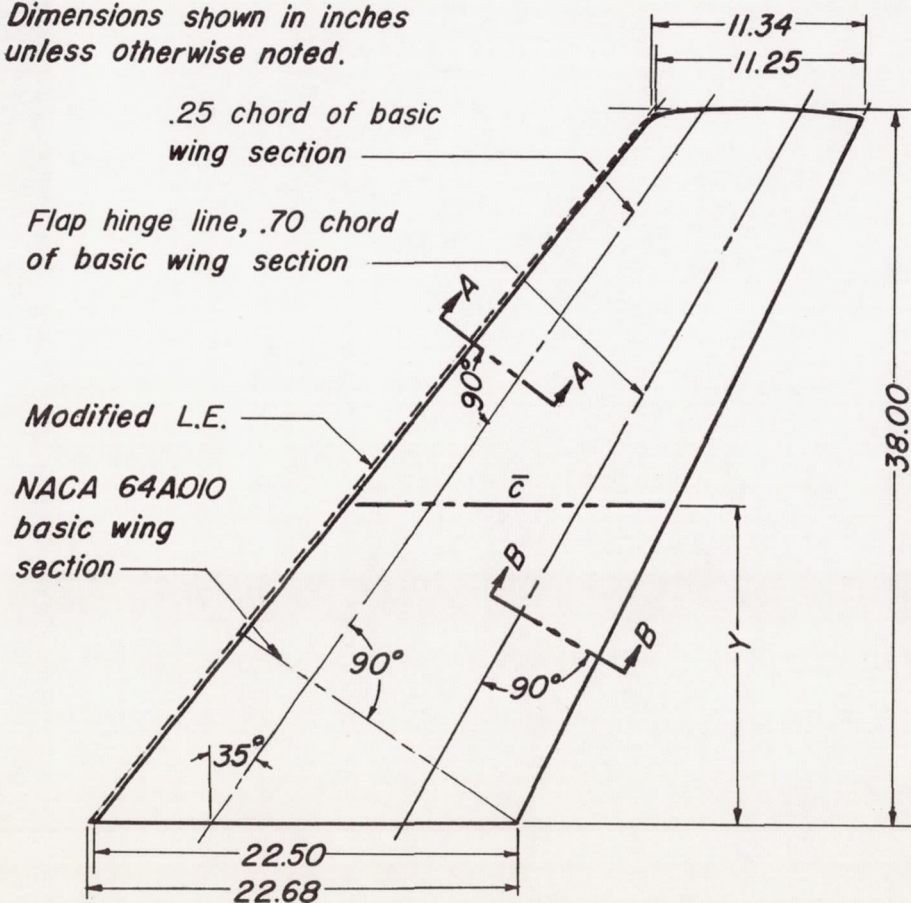
TABLE I. - COORDINATES FOR THE NACA 64A010 AIRFOIL SECTION
AND THE MODIFIED NACA 64A010 AIRFOIL SECTION

[All dimensions in percent of chord of original NACA 64A010 airfoil]

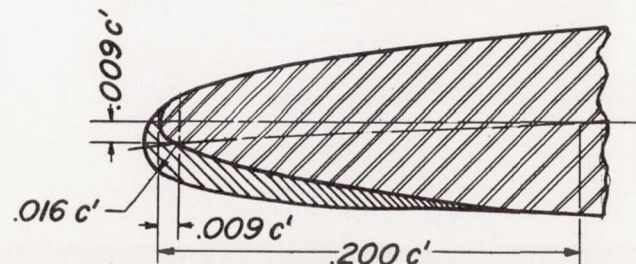
Coordinates				
NACA 64A010		Modified NACA 64A010		
Station	Ordinate	Station	Ordinates	
	Upper and lower		Upper	Lower
-	-	-0.72	-0.87	-0.87
-	-	-.71	-.75	-1.02
-	-	-.50	-.09	-1.69
-	-	-.25	.23	-2.03
0	0	0	.46	-2.25
.50	.80	.50	.82	-2.54
.75	.97	.75	.97	-2.67
1.25	1.23	1.25		-2.88
2.50	1.69	2.50		-3.25
5.00	2.33	5.00		-3.58
7.50	2.81	7.50		-3.72
10.00	3.20	10.00		-3.81
15.00	3.81	15.00		-3.96
20.00	4.27	20.00		
30.00	4.84	30.00		
40.00	5.00	40.00		
50.00	4.68	50.00		
60.00	4.02	60.00		
70.00	3.13	70.00		
80.00	2.10	80.00		
90.00	1.06	90.00		
95.00	.54	95.00		
100.00	.02	100.00		
L.E. radius: 0.687 T.E. radius: 0.023		L.E. radius: 1.600 T.E. radius: 0.023		



Dimensions shown in inches
unless otherwise noted.

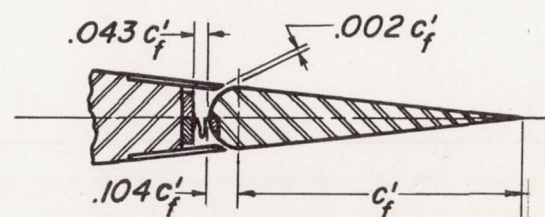


	Basic wing	Modified wing
Aspect ratio	4.5	4.464
Taper ratio	0.5	0.5
Area semispan	4.443 ft ²	4.489 ft ²
Flap area	1.204 ft ²	1.204 ft ²
$\bar{c}$	1.458 ft	1.470 ft
Y	1.408 ft	1.409 ft



See table I
for coordinates

Section A-A



Section B-B

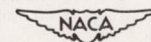


Figure 1.- Geometric characteristics of the model.

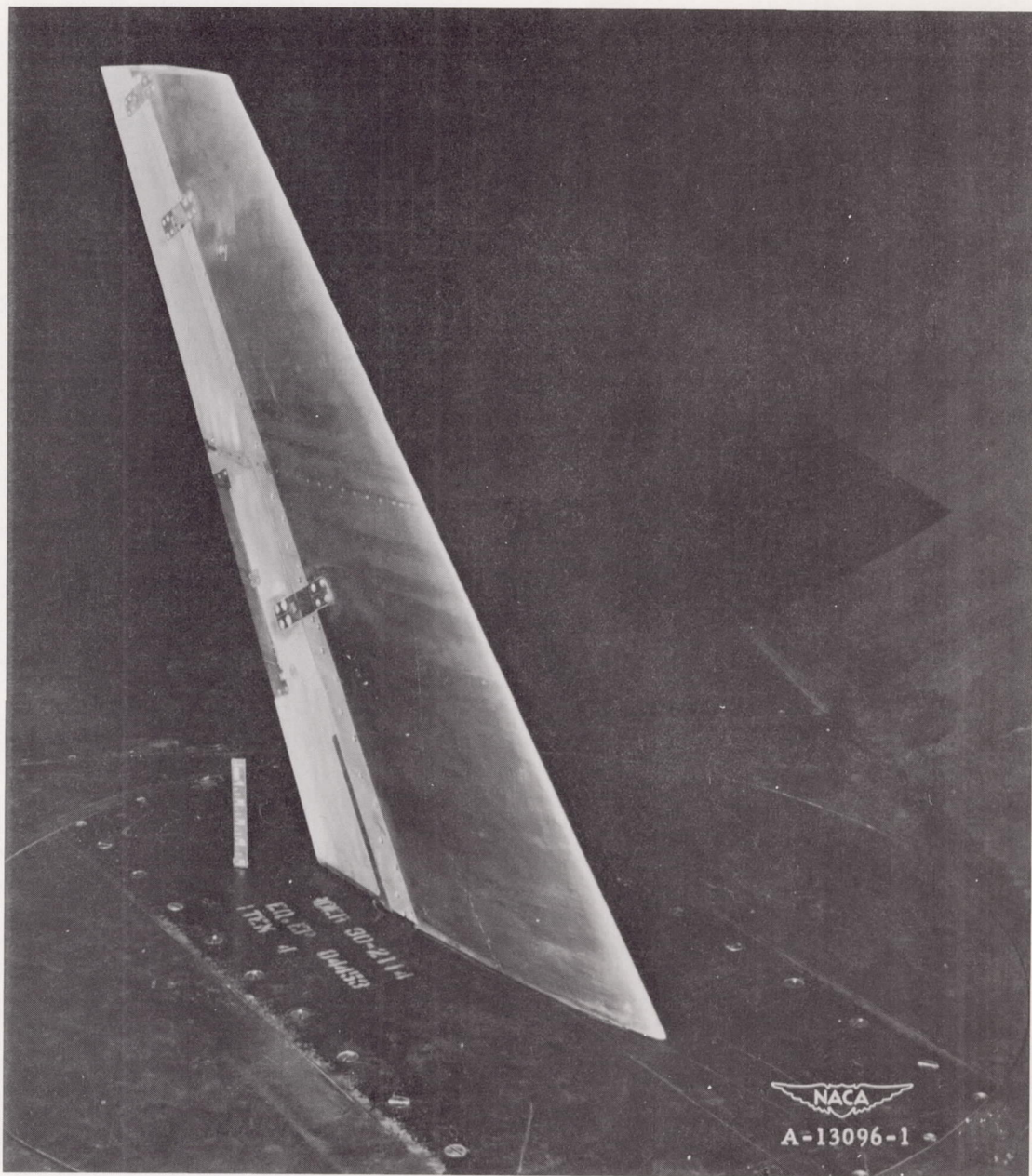


Figure 2.— Photograph of the wing mounted in the Ames 12-foot pressure wind tunnel.

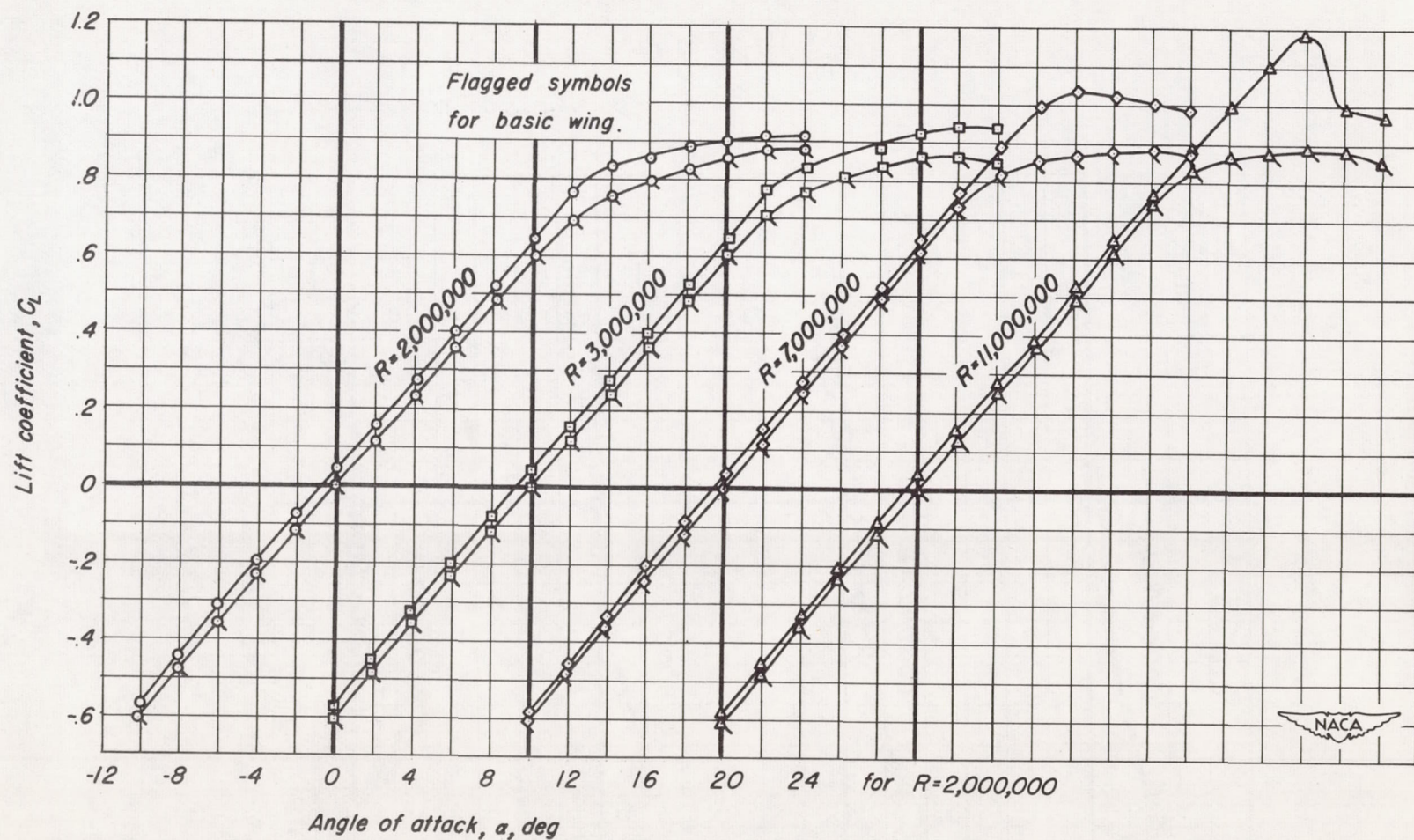
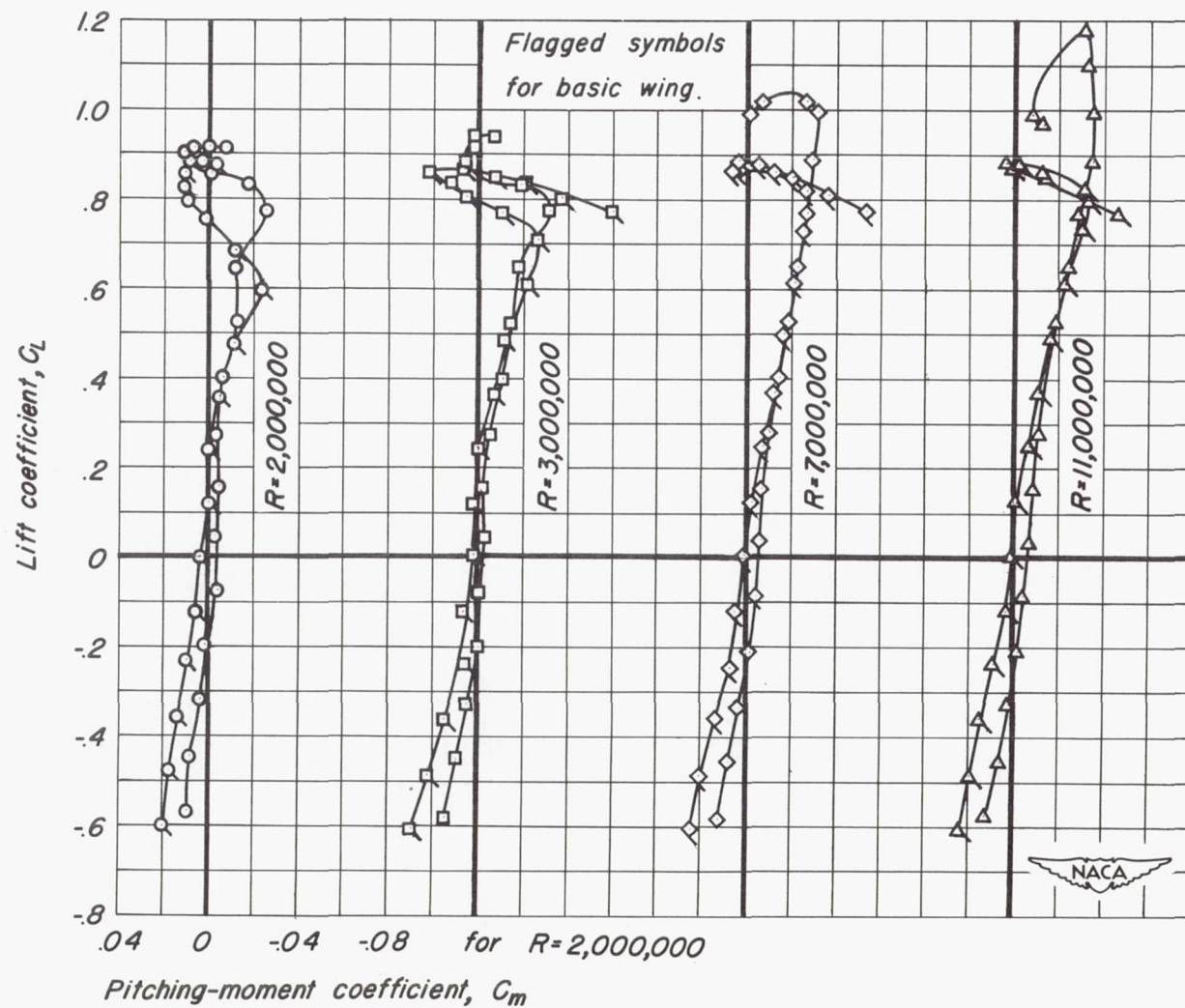
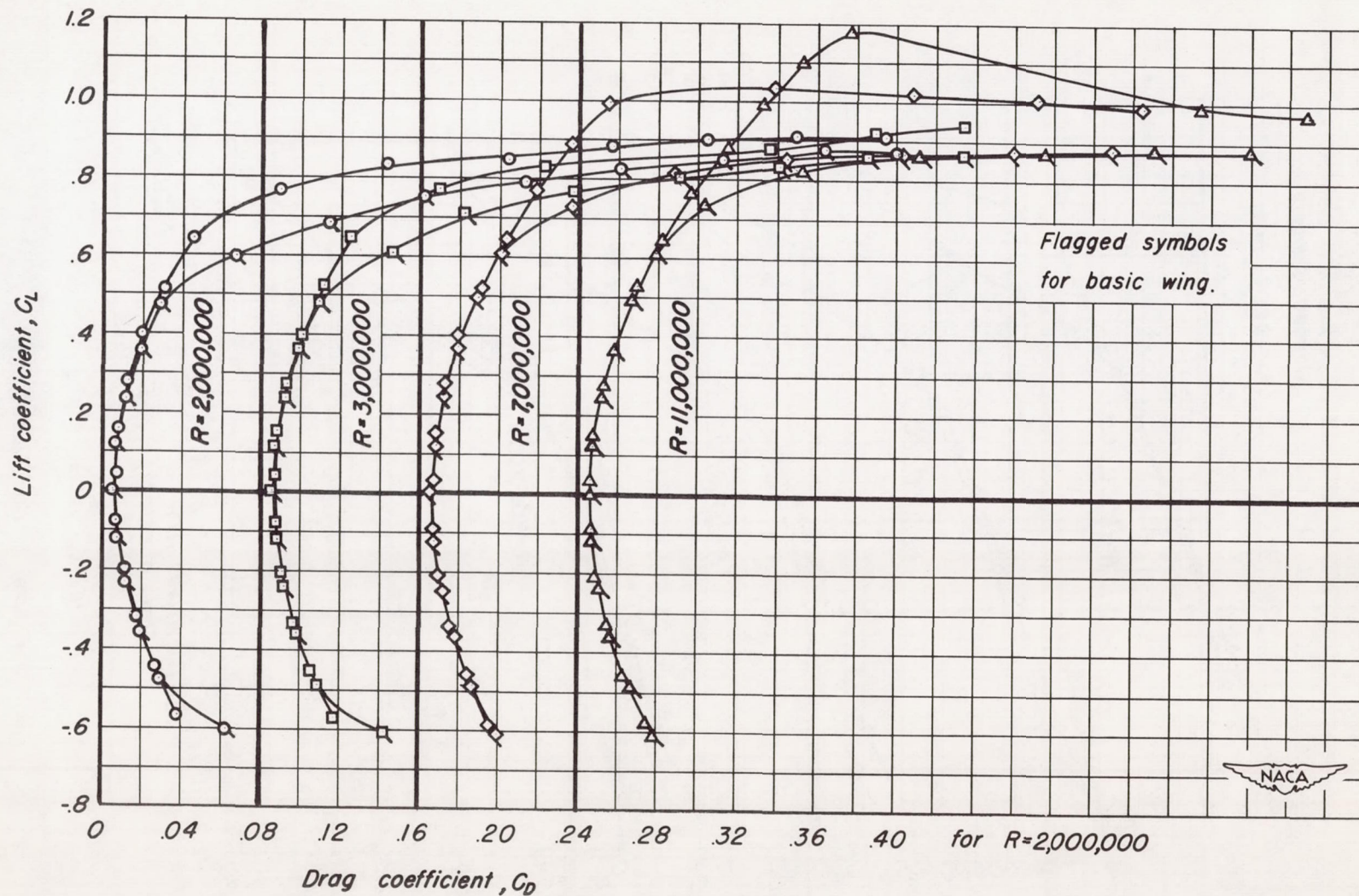
(a) C_L vs α .

Figure 3.- The effect of Reynolds number on the low-speed aerodynamic characteristics. M , 0.21.

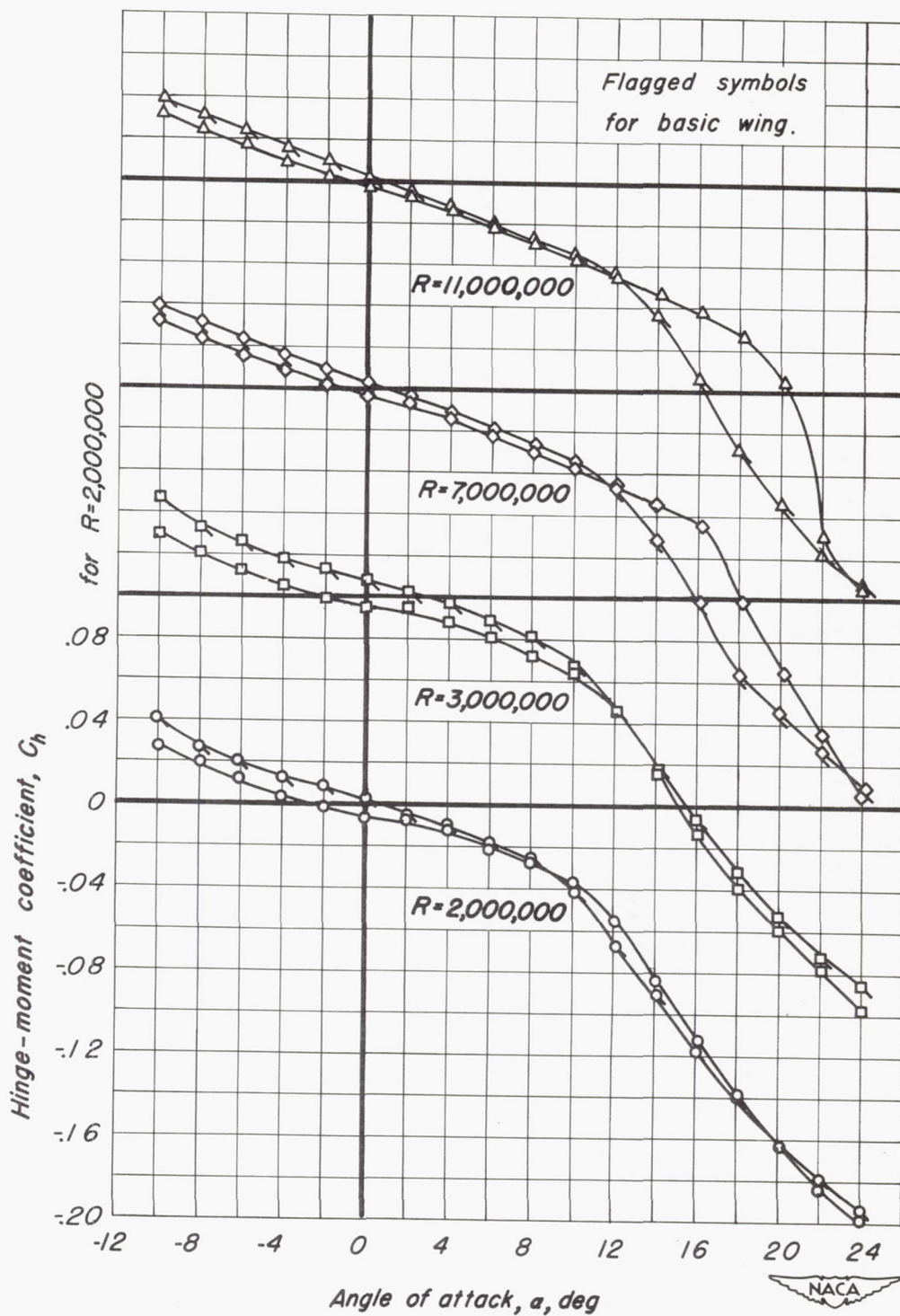


(b) C_m vs C_L .

Figure 3.- Continued.



(c) C_D vs C_L .
Figure 3.- Continued.



(d) C_h vs α .

Figure 3.- Concluded.

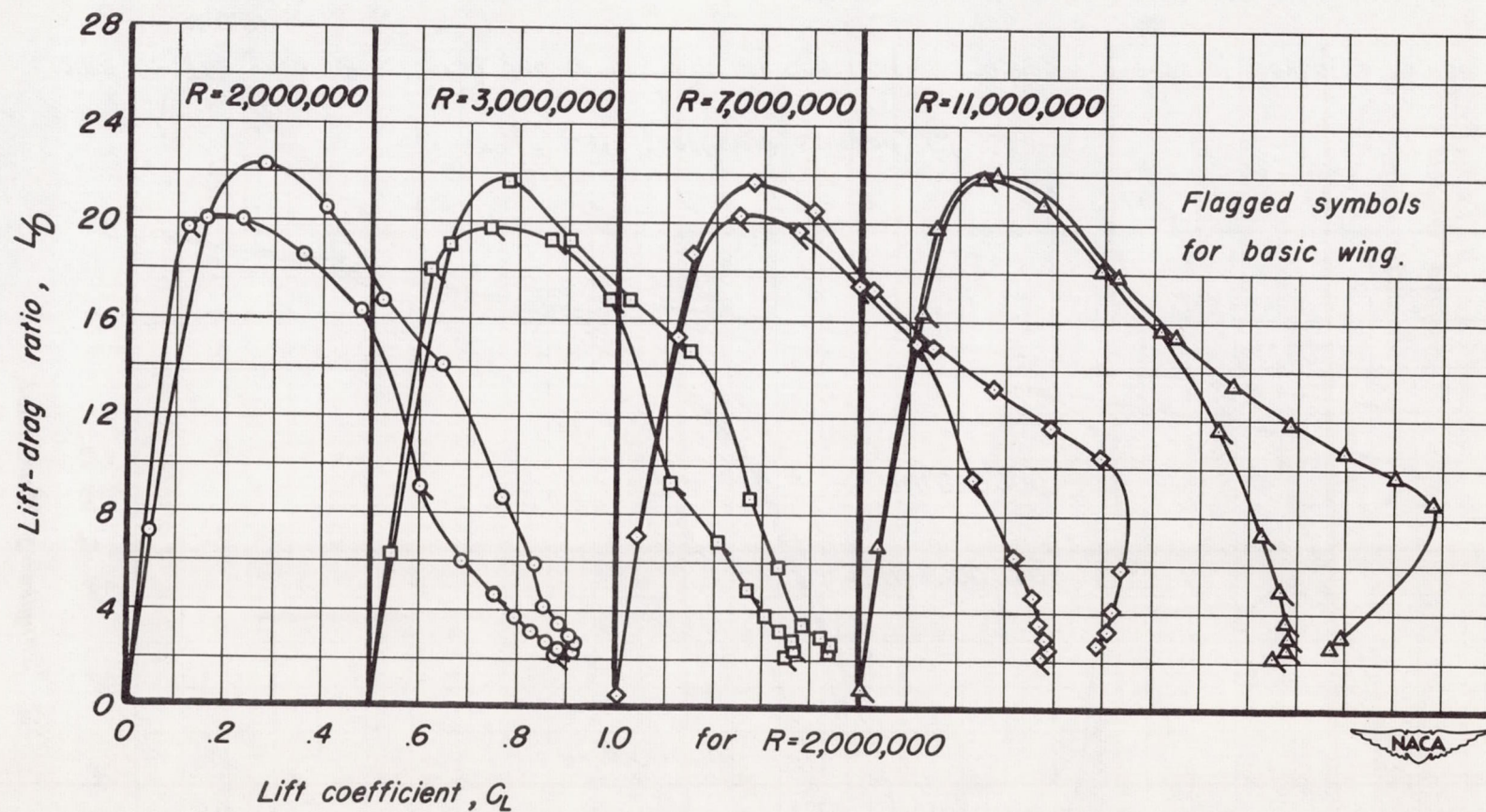


Figure 4.- The variation of lift-drag ratio with lift coefficient at several Reynolds numbers. $M, 0.21$.

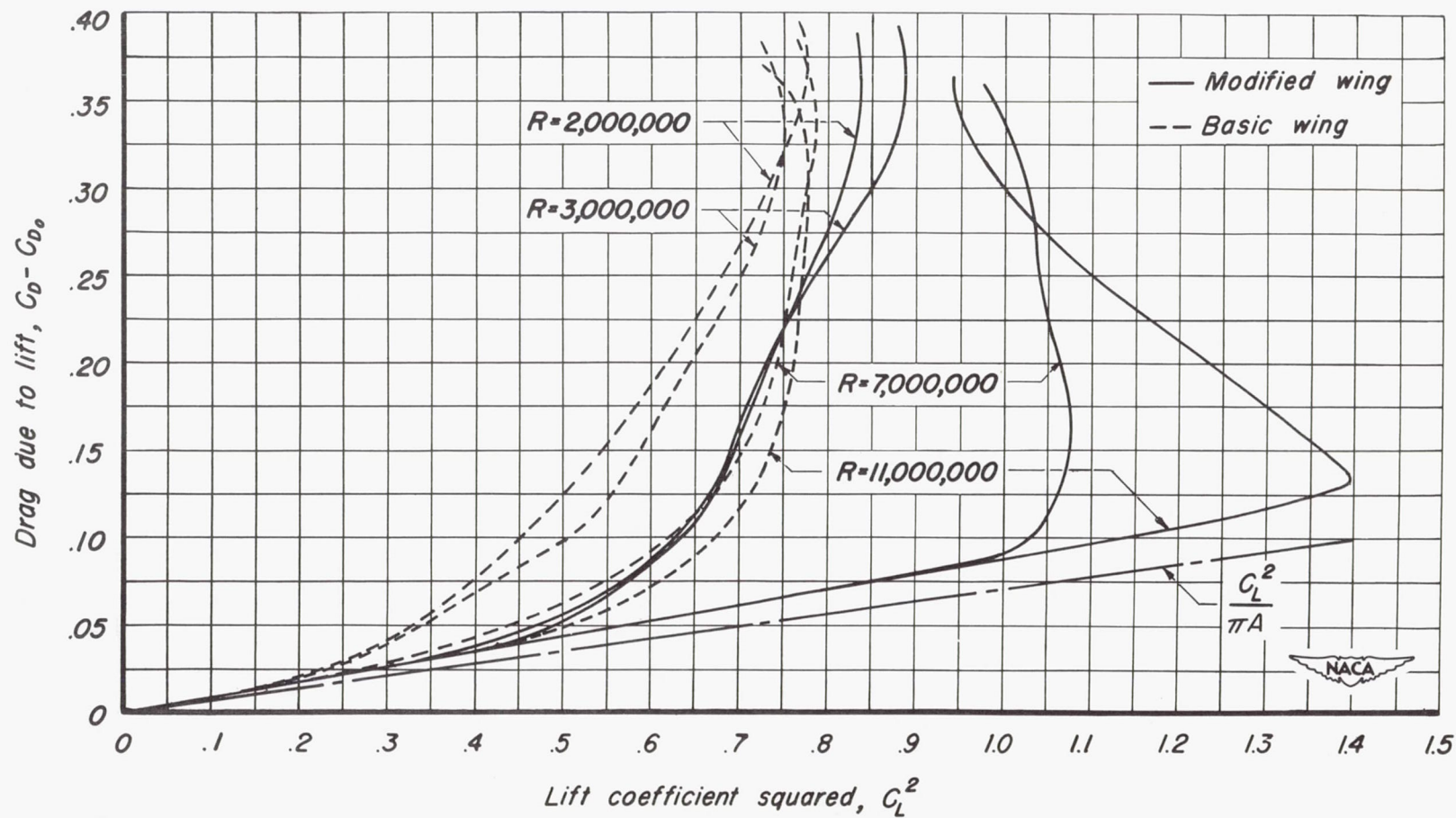
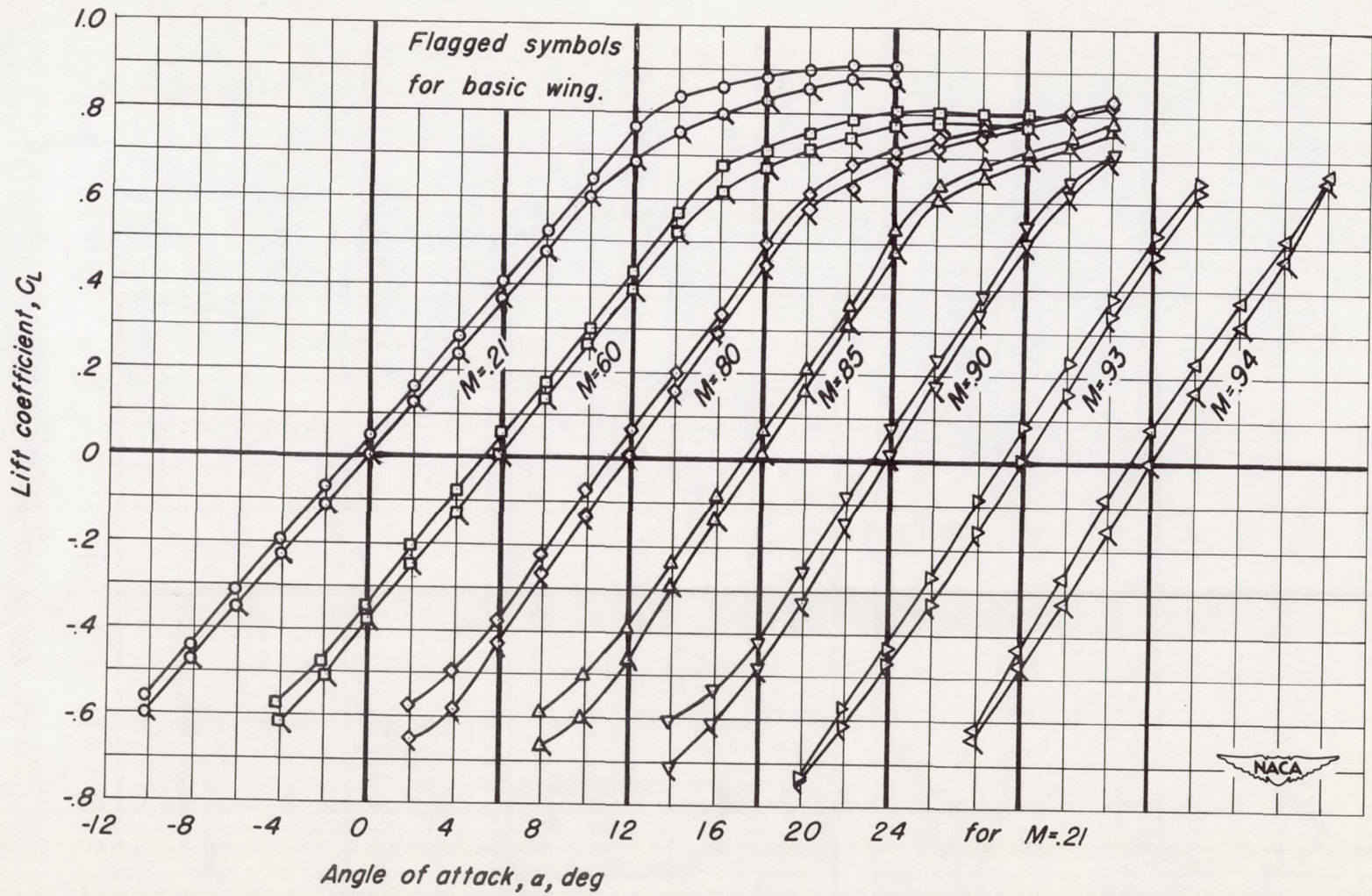
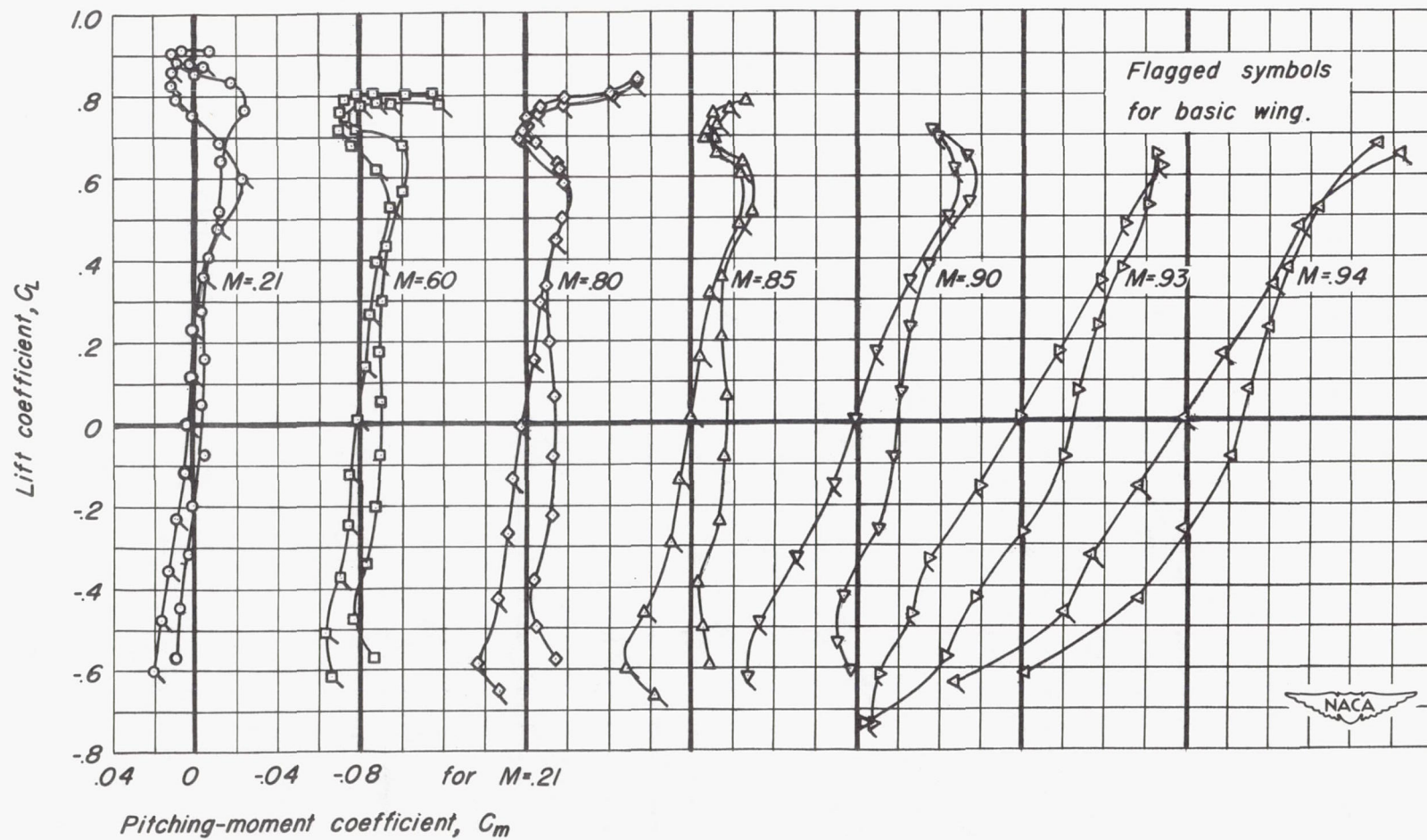


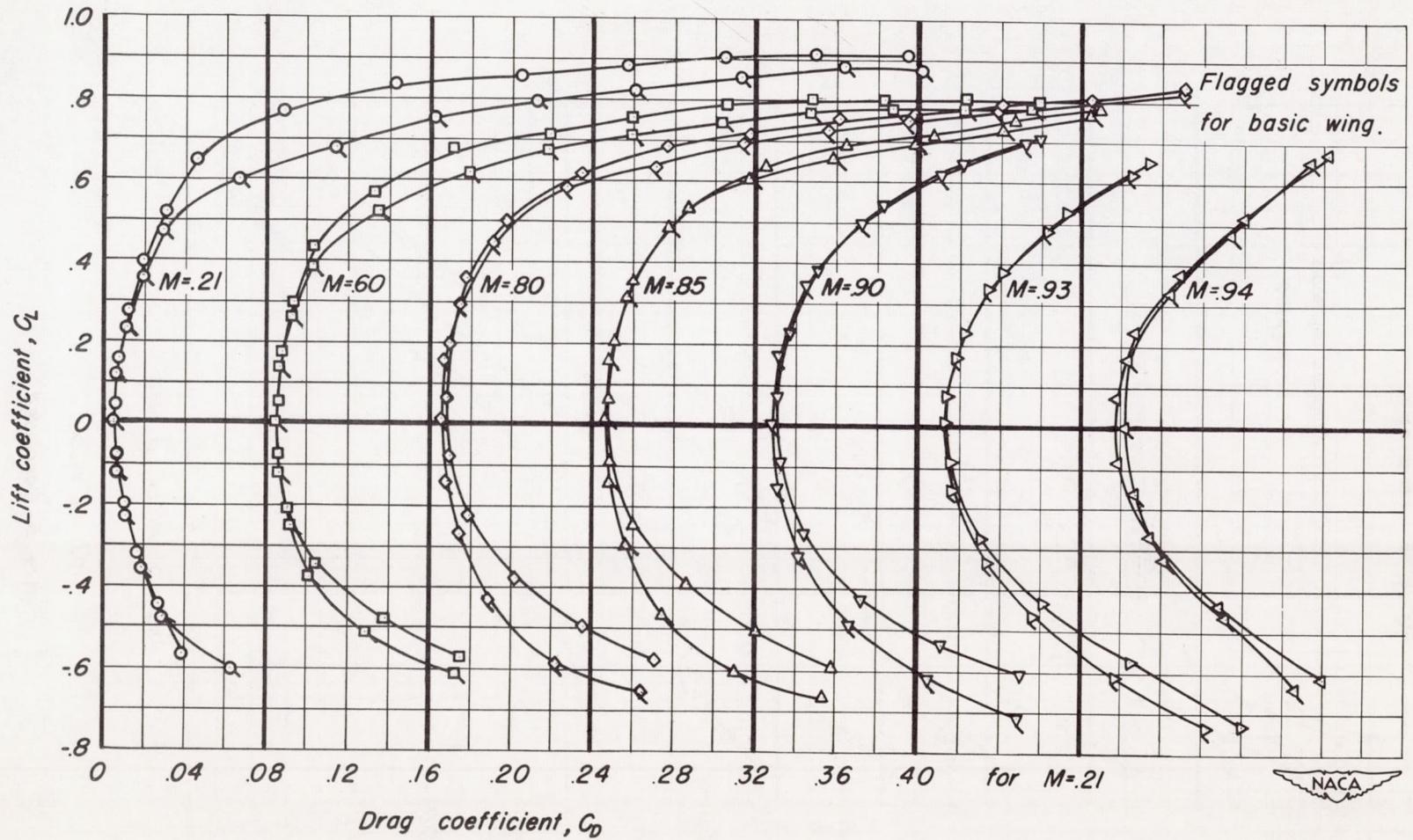
Figure 5.- The variation of drag due to lift with lift coefficient squared at several Reynolds numbers.
M, 0.21.

(a) C_L vs α .Figure 6.-The effect of Mach number on the aerodynamic characteristics. R , 2,000,000.



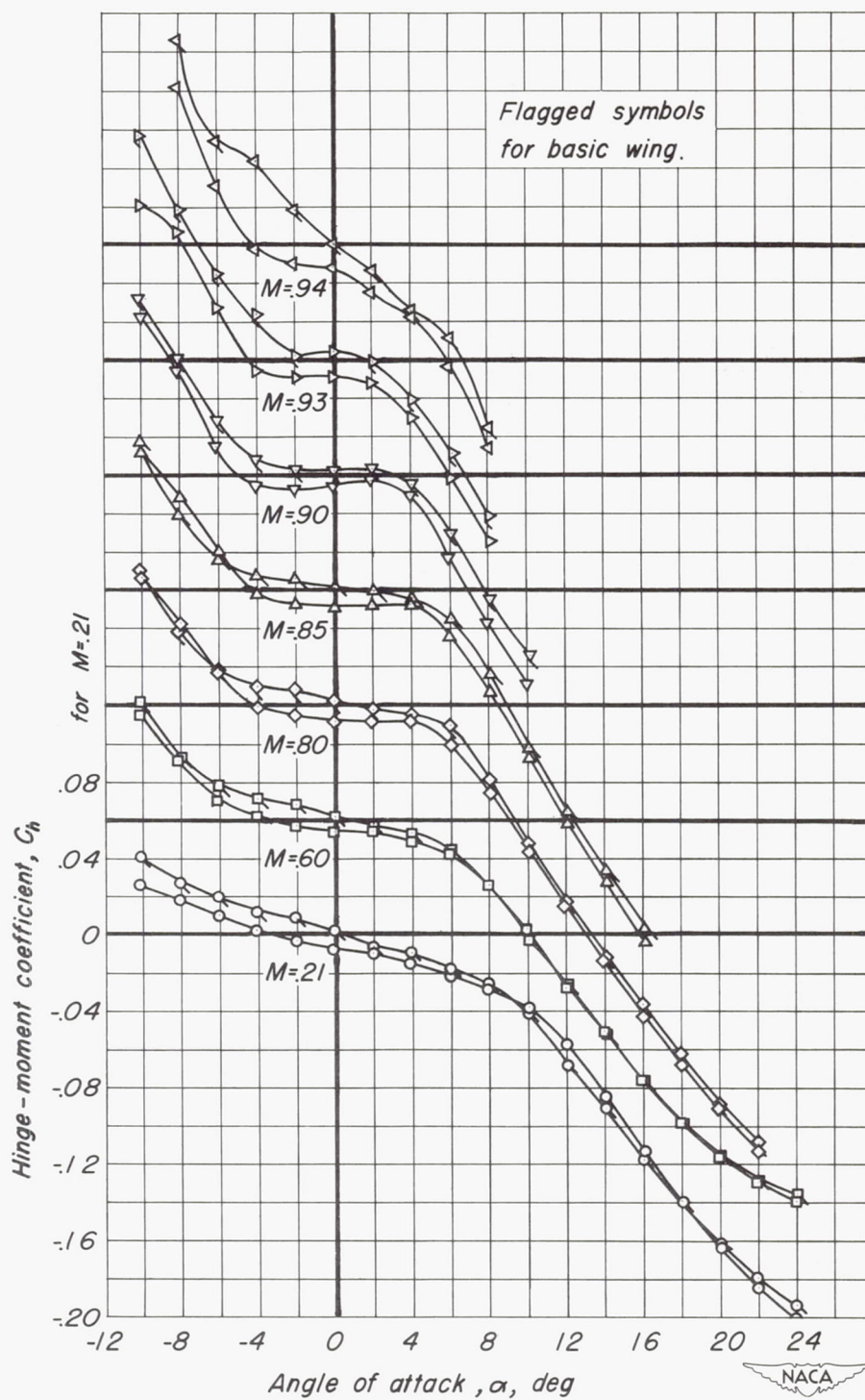
(b) C_m vs C_L .

Figure 6.- Continued.



(c) C_D vs C_L .

Figure 6.- Continued.



(d) C_h vs α

Figure 6.- Concluded.

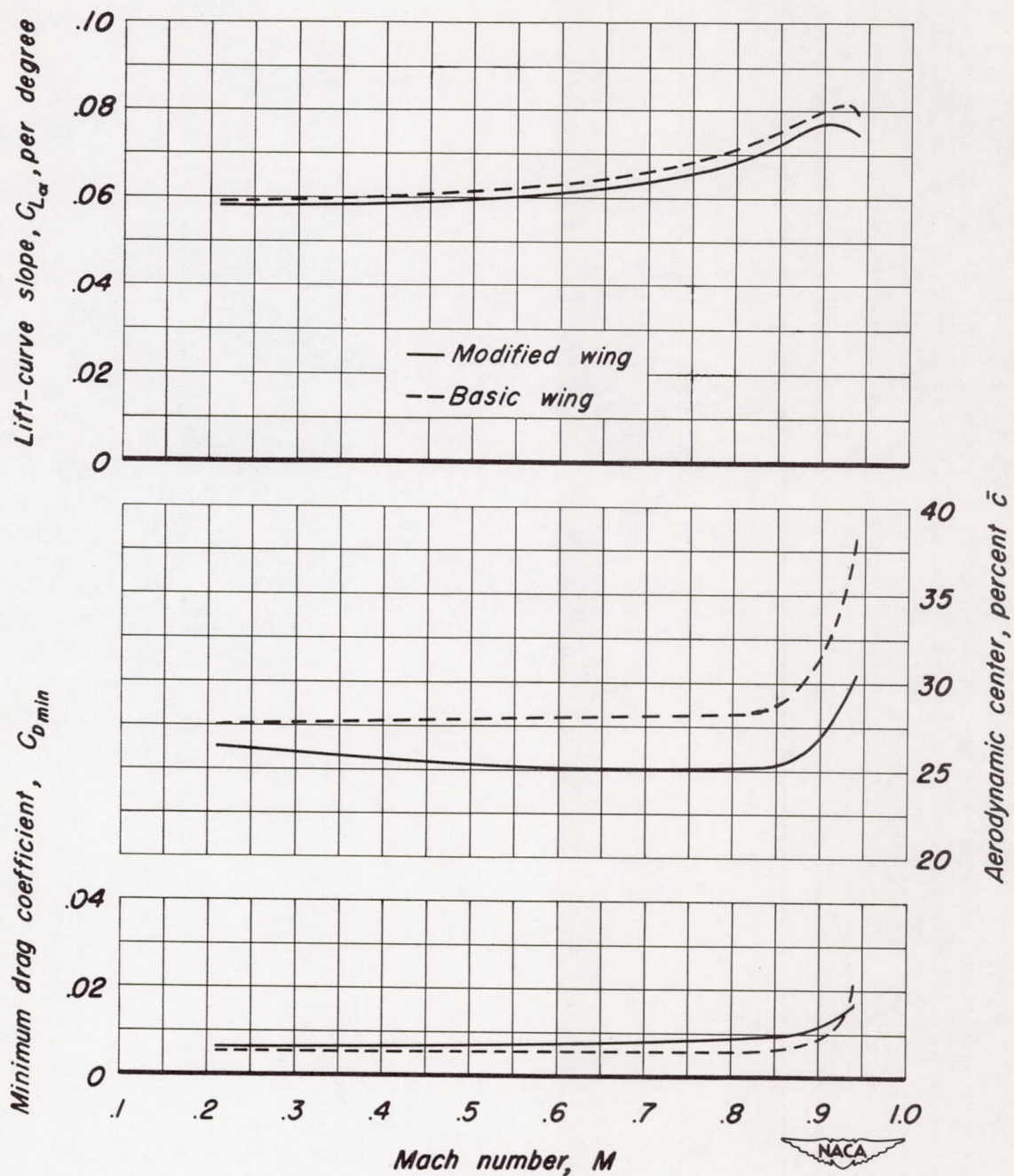


Figure 7.— The variation with Mach number of lift-curve slope, aerodynamic center, and minimum drag coefficient. R , 2,000,000.